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Measurement of artificial-satellite spectra with a small telescope

M. Lelièvre
M. P. Lévesque
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Defence R&D Canada – Valcartier
Technical Report
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Canada

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Authors

Mario Lelièvre, Martin P. Lévesque, Sylvie Buteau

Approved by

Jean-Marc Garneau
Section Head, Optronic Surveillance

Approved for release by

Christian Carrier
Chief Scientist

Abstract

In the surveillance of space context, satellites positions must be frequently reacquired to maintain an accurate knowledge of their orbital parameters. However, acquiring several satellites in the same image (particularly in the geostationary belt) is not rare and it is often not possible to definitively identify each one of them. In such a case, important errors can be introduced into the database if incorrect associations are made. Therefore, being able to correctly identify each satellite is very important in order to make valid updates.

To this end, the experiment described in this report tried to demonstrate that 1) satellites can be identified by using their spectral signatures and 2) these spectra can be acquired with a small telescope. However, even if color differences could be observed, the measuring system was not sensitive enough to properly demonstrate this hypothesis, and too few observations were performed (with only the brightest geostationary satellites) during the period when the telescope was available for this experiment. This report presents the few results that were obtained and explains the encountered difficulties. It also makes recommendations about the minimal equipment requirements to obtain results that could properly validate the experimental hypotheses.

Résumé

Dans le contexte de la surveillance de l’espace, la position des satellites doit être acquise fréquemment pour maintenir une connaissance précise de leurs paramètres orbitaux. Cependant, il n’est pas rare d’acquérir plusieurs satellites dans la même image (particulièrement dans la ceinture géostationnaire) et il n’est souvent pas possible d’identifier chacun d’eux. Dans de tels cas, des erreurs importantes peuvent être introduites dans la base de données si de mauvaises associations sont faites. Donc, il est très important de pouvoir identifier correctement tous les satellites afin de faire correctement les mises à jour.

À cette fin, l’expérience décrite dans ce rapport a tenté de démontrer que 1) les satellites peuvent être identifiés en utilisant leurs signatures spectrales et 2) ces spectres peuvent être acquis au moyen d’un petit télescope. Cependant, même si des différences de couleurs ont été observées, le système de mesure n’était pas suffisamment sensible pour démontrer réellement cette hypothèse et trop peu d’observations ont été faites (avec seulement les satellites géostationnaires les plus brillants) pendant la période où le télescope était disponible pour cette expérience. Ce rapport présente les quelques résultats qui ont été obtenus et explique les difficultés qui ont été rencontrées. Il fait aussi des recommandations sur l’équipement minimal requis qui devrait être utilisé si l’expérience devait être refaite.

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Executive summary

Canada (more particularly DND/DSpaceD) participates in the SSN (Space Surveillance Network) surveillance of space effort by operating a number of ground-based observatories. Since the closure of the Baker-Nunn stations, this task is now performed by the observation stations called the 'DSpaceD Concept Demonstrator' or more commonly CASTOR.

In the surveillance of space context, satellite positions must be reacquired frequently to maintain an accurate knowledge of their orbital parameters. However, acquiring several satellites in the same image (particularly in the geostationary belt) is not rare and it is frequently difficult to positively identify a particular satellite. In such a case, important errors can be introduced into the database if incorrect associations are made. Therefore, being able to identify each satellite is very important in order to make valid updates.

To this end, the experiment described in this report tried to demonstrate that satellites have spectral signatures that can be used for their identification. However, even if color differences can be observed, the measuring system was not sensitive enough to properly demonstrate this hypothesis and too few observations were performed (with only the brightest geostationary satellites) during the period when the telescope was available for this experiment. This report presents the few results that were obtained, explains the encountered difficulties and makes recommendation regarding the minimal equipment requirements to obtain results that could properly validate the experimental hypotheses.

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Sommaire

Le Canada (plus particulièrement via le MDN/DSpaceD) participe à l'effort de surveillance de l'espace du SSN (Space Surveillance Network) en exploitant un certain nombre de stations d'observation terrestres. Depuis la fermeture des stations Baker-Nunn, la relève est maintenant assurée par les stations d'observation appelées 'DSpaceD Concept Demonstrators' ou plus communément CASTOR.

Dans le contexte de la surveillance de l'espace, la position des satellites doit être acquise fréquemment pour maintenir une connaissance précise de leurs paramètres orbitaux. Cependant, il n'est pas rare d'acquérir plusieurs satellites dans la même image (particulièrement dans la ceinture géostationnaire) et il n'est souvent pas possible d'identifier chacun d'eux. Dans de tels cas, des erreurs importantes peuvent être introduites dans la base de données si de mauvaises associations sont faites. Donc, il est très important d'être capable d'identifier tous les satellites afin de faire correctement les mises à jour.

À cette fin, l'expérience décrite dans ce rapport a tenté de démontrer que les satellites ont leurs signatures spectrales propres qui peuvent être utilisées pour les identifier. Cependant, même si des différences de couleurs ont été observées, le système de mesure n'était pas suffisamment sensible pour démontrer réellement cette hypothèse et trop peu d'observations ont été faites (avec seulement les satellites géostationnaires les plus brillants) pendant la période où le télescope était disponible pour cette expérience. Ce rapport présente les quelques résultats qui ont été obtenus, explique les difficultés qui ont été rencontrées et fait des recommandations sur l'équipement minimal requis qui devrait être utilisé si l'expérience devait être refaite.

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1. Introduction

The Soviet Union launched the first artificial satellite, Sputnik 1, in 1957. Since this time, about 40 other countries (including Canada) have developed, launched, and operated satellites. Today, close to eleven thousand objects (satellites, boosters, satellite remnants) larger than ten centimeters in diameter/cross-section are orbiting the Earth. On a smaller scale, objects ranging between one centimeter and ten centimeters and those smaller than one centimeter account for 100 000 and ten of millions, respectively.

An important objective consists in identifying satellites, which populate space in a still increasing number. It is a worldwide objective to build an updated database of each orbiting object. The Space Surveillance Network (SSN) uses large telescopes and radars located all around the world to maintain tracks of as many satellites as possible. Unfortunately, they are not sufficient to perform this task when taking into account the large number of satellites to observe continuously combined with rapid variations of satellite orbital parameters. Those orbital characteristic changes account for many missing objects and are mostly related to atmospheric drag, solar wind, moon and planetary gravitation field, Earth oblateness, etc.

Over the past few years, small ground-based telescopes (smaller than one meter mirror aperture) joined the SSN and made it possible to observe, track and identify more satellites at low cost. Small telescopes also help to update (with better accuracy) what we know about the orbital parameters of each satellite. They also help to identify new and re-acquire missing objects.

In Canada, such a ground-based system is currently in use. The Space Concept Demonstrator (CD) is part of the Canadian Surveillance of Space Project (SoSP).

The CD consists of three optical sensors initially named CASTOR (for Canadian Automated Small Telescope for Orbital Research) located across Canada (CASTOR-V at **V**alcartier-Quebec, CASTOR-K at **K**ingston-Ontario and CASTOR-S at **S**uffield-Alberta) and remotely controlled from a Sensor Operations Center (SOC) located at DRDC Ottawa (Refs. 1 to 3). Using three geographically separated sensors raises the probability of obtaining clear sky conditions at (at least) one of the three sites every day. The CASTOR-V sensor (on which this document is based) is located at 46º 52’ 31.98’’ of latitude North; 71º 28’ 14.48’’ of longitude West and at an elevation of 177 m.

The *SoSP* main objective will be to point, track, identify and update a database of most Earth orbiting objects larger then 10 cm. Moreover, most of the observation process linking the three observatories would have to be automated and optimized to maximize the number of pointed satellites in any single night. Besides the pointing and tracking process, automated algorithms are under development for automatically discriminating and identifying what might be a satellite signature in a given image.

Like most observing tools used around the world for identifying satellites, the SoSP identification will be based on imagery techniques. However, other techniques, which are based on the spectral nature of light, may help to identify satellite in a much more accurate manner. Since 2002, the CASTOR-V system has been equipped with a spectrometer to see how spectroscopy combined with the actual system could help in identifying Earth-orbiting satellites. The goal of this document is to describe the limits of CASTOR-V in performing satellite spectroscopy.

This work was performed between May 2004 and June 2006 under WBE 15et13, ‘Surveillance of Space with Small Telescope’.

2. Problematics

There are so many parameters that allow characterizing a satellite (shape, orbit, surface characteristics, etc.) that, once detected, one may think that it is straightforward to identify it. However, considering the quantity of space debris combined with the very limited sensor capabilities, space situation awareness can very quickly become confused and the identification of a specific RSO (Resident Space Object) is not at all a straightforward task. When every classical approach has failed, spectroscopy may provide a tool that can help in that identification task.

Before describing the spectral measurement method, let us see how the satellites are classified first, how they are usually detected (and then identified by default) and how the spectroscopy could be used in specific cases to reduce the confusion.

2.1 Types of orbits and satellite classification

Satellite orbits may be circular or elliptical. They also vary in altitude, some circular orbits being located just above the atmosphere at an altitude of about 250 km, while others are found more than 36 000 km above Earth surface. Moreover, the altitude of highly elliptical satellites may vary during one single revolution from a few hundred kilometers up to 40 000 km. This is the case with the Russian Molnyia satellites which are characterized by high inclined orbits and perigee and apogee altitudes of 450-600 km and 40 000 km, respectively. This makes it possible for Molnyia satellites to spend most of their time (up to 8 hours) in the Northern hemisphere during their nearly 12 hour orbits. This behaviour results from a physical rule linking gravity and velocity and stating that the greater the altitude, the longer the orbital period.

Although many types of orbits exist, most artificial satellite orbits may be categorized in one of the following types: 1- high altitude and circular orbit; geostationary; 2- high altitude and highly elliptical orbit: Molnyia, 3- medium altitude; 4- polar sun-synchronous low Earth orbit (LEO) and 5- low altitude.

A high altitude, geostationary satellite lies above the equator at an altitude of about 36000 km. Such a satellite orbits Earth with a 24 hour period. Thus, as seen from Earth, the satellite always appears at the same place in the sky – this is ideal for broadband communications with relatively un-sophisticated ground reception stations such as satellite TV.

A medium altitude orbit satellite has an altitude of about 20 000 km and an orbital period of 12 hours. The high altitude of these satellites (as for geostationary ones), above the Earth atmosphere, provides high orbital stability and high coverage. This makes these satellites ideal for navigation like the GPS ones.

A sun-synchronous, polar orbit has a fairly low altitude and passes close to the north and south poles (typically with an inclination of 98 degrees). A slow drift of the orbit's position is coordinated with Earth's movement around the sun in such a way that the satellite always crosses the equator at the same local time on Earth. Because the satellite flies over all latitudes, its instruments can gather information on almost the entire surface of the Earth. This makes those satellites very suitable for studying how natural cycles and human activities affect the Earth's climate. The altitude of its orbits is typically between 700 and 800 km, and the orbital period is between 90 and 100 minutes.

A low altitude orbit is just above Earth's atmosphere, where there is almost no air to cause drag on the spacecraft and reduce its speed. Observation satellites that point toward deep space and provide scientific information generally operate in this type of orbit. This is the case of the Hubble Space Telescope, which lies at 610 km above the Earth. Lower orbits have more serious atmospheric drag but can still be used for short term missions (like for the space shuttles) or for satellites that require regular visits and periodic maintenance like the International Space Station. At lower altitude, active thrusters are required to maintain the satellite orbit.

Artificial satellites are also classified according to their mission. There are six main types of artificial satellites: 1- scientific research, 2- weather, 3- communication, 4- navigation, 5- Earth observing, and 6- military.

2.2 Satellite detection and identification processes

Nowadays, the technique mostly used for satellite detection (and by default identification) consists in acquiring satellite images (or radar echoes) with ground-based observatories. By knowing satellite orbital parameters, its position can be predicted fairly accurately at a given time. Then the acquired images confirm the satellite presence and the position errors are recorded and used to update the orbital parameters.

The North American Aerospace Defence Command (NORAD) keeps an updated database of all known Earth-orbiting objects larger then 10 cm. This represents thousands of satellites and satellite remnants. NORAD allows external users to access these orbital parameters, which are distributed by NASA in a file format called 'Two-Line-Element set' (TLE). Using the appropriate software, a telescope can point and track a satellite described by a given TLE.

When observing a satellite, the image acquisition can be performed in sidereal tracking or satellite tracking (Figure 1) mode. In the first case, stars appear as point sources in the images and the satellite appears as a streak of finite length. The length of the streak depends on parameters such as satellite apparent motion (relatively to the celestial background) and exposure time.

When tracking a satellite (the second case), the telescope movement is linked to the satellite orbital parameters. In those images, a satellite appears as a point source and stars become streaks. In satellite tracking mode, the intensity measured for a given satellite depends on the satellite reflectance, distance, size, phase angle and is directly proportional to the exposure time. It also depends on environmental parameters (sky transparency, darkness and humidity level) and this is why the sky transparency is monitored by measuring a calibration star located in the same sky area as the acquired satellite. The measured intensity also depends on the characteristics of the equipment system (telescope f/number, CCD camera, etc) which is well characterized.

Both sidereal and satellite tracking provide physical input that may be used for satellite identification and specification. Both can serve to achieve photometric study on a satellite. In sidereal tracking the length, orientation and position (relatively to the star positions) of the streak can be used to update the satellite orbital characteristics. Also, variation of intensity measured in the streak may serve to assess dynamical satellite characteristics such as its spinning movement. Satellite tracking imagery, when used with filters, may serve to distinguish satellites from their color reflectance. Indeed, depending on the satellite composition (solar panel, paint composition, coating), two satellites may not reflect the light at a given wavelength with the same efficiency. Satellites can be distinguished by measuring the ratio of light passing through filters of different colors (red, blue).

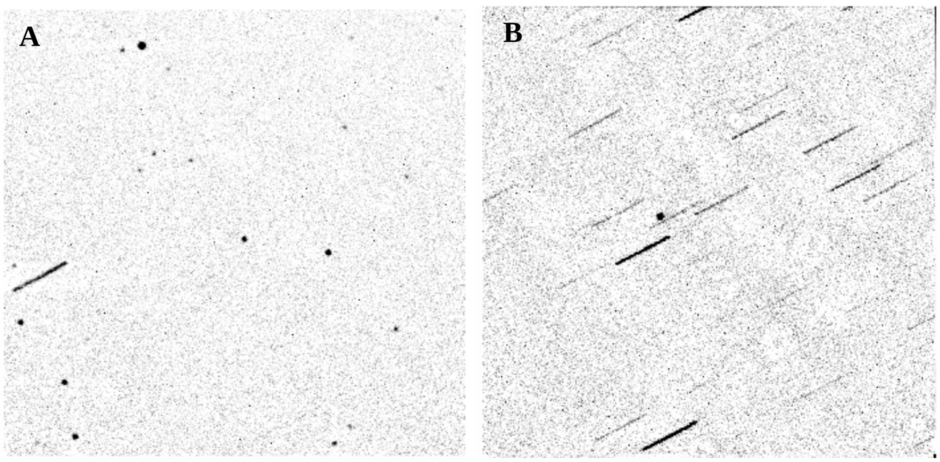

Figure 1, *A) Sidereal tracking image acquired with Apogee CCD. The streak in the middle left represents the geostationary satellite Amazonas. B) Satellite tracking image acquired with Apogee CCD. The unique point like source in the image is the satellite Amazonas. The streaks represent the stars.*

2.3 Usefulness of spectroscopy

Although imagery remains a good method for satellite identification and monitoring, there are other approaches that may help to more accurately measure satellite characteristics and to distinguish them. One of the emerging difficulties of satellites discrimination is related to their increasing number. It is not rare, when imaging a small field of view, to obtain two or more satellites of similar brightness in a single image (Figure 2). In those cases, it could become more difficult to make a correct identification by using standard approaches, i.e., by expected position, photometry and tumbling period. Other approaches must be considered. One of these is based on the spectral signature of satellites. The spectrum acquisition has to be done in satellite tracking mode since the satellite must be maintained into a very narrow window, which corresponds to the input spectrometer slit.

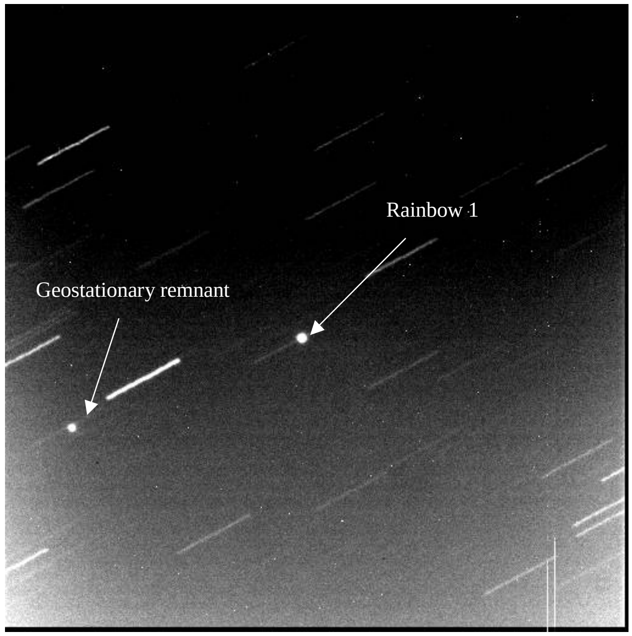

Figure 2. *Image obtained with the Apogee camera showing two satellites in a 21.6' x 21.6' field of view*

If satellites were perfectly white Lambertian reflectors, their spectra would be exactly the same as the sun. However, this is not the case, all materials absorb, emit and reflect light in a proportion that depends on the wavelength and reflective properties of the material. For example, two satellites painted with different colors would reflect and absorb light differently. A black-coated satellite would absorb a large proportion of the visible spectrum in comparison with a white-coated satellite, but would present a more intense infrared signature. The satellite reflectance may be studied with imagery acquired with colour filters, but a spectrometer could be used to obtain a more detailed satellite spectra. Indeed, to obtain the same information provided by a single spectrum would require several images and several filters. Furthermore, the illumination conditions can change from an exposure (image) to another while all the spectral bands would be equally acquired.

The following chapters describe the evaluation procedure used to study the satellite identification capability based on spectrum acquired with the CASTOR-V telescope. First, the main characteristics of the observation system are presented. The next chapter describes the calibration steps that have been performed on the telescope and instruments prior to data acquisition. Afterwards, some results obtained with geostationary satellites are presented. Finally, these results (of limited scope) are analysed and this study leads to a critique of the capabilities, limits and deficiencies of the CASTOR-V system for measurement of satellite spectra. At the end, some suggestions are made regarding improvements that could be done to obtain a system suitable for the task of spectral acquisition.

3. Description of the acquisition system

The spectral measurements performed with the CASTOR-V installation were acquired using an amateur class small telescope, the main goal being to see if such low cost equipment could be suitable for such a mission. This chapter describes the various components of the observatory.

3.1 Observatory

CASTOR-V is located at the following coordinates: latitude = 46º 52’ 31.98’’ North, longitude = 71º 28’ 14.48’’ West, altitude = 177 m and is approximately at a distance of 30 km from Quebec City. Although the proximity of the city lights affect photometric conditions, the distance from the main source of polluting light is thought to be large enough to image point objects as dim as magnitude 16 in 10 seconds with a signal-to-noise ratio better than 1. This theoretical assumption will be verified in this document.

All the equipment of CASTOR-V is located in a 10.5 ft diameter spherical steel dome manufactured by Ash Domes (Figure 3). The telescope and observing instruments are located on the first floor and are positioned by a dome control system manufactured by Meridian Controls. There is also a main computer on the first floor allowing remote control from DRDC Ottawa. A small control room equipped with a PC is located on the main floor and allows for control of the telescope locally.

Figure 3. *External view of CASTOR-V*

3.2 Telescope and mount

A Celestron Model CG-14 (a 14-Inch Aperture, Schmidt-Cassegrain Reflecting Telescope) is used to perform observations (see Table 1 for physical characteristics of the telescope). The telescope is mounted on a Paramount 1100GT German-Equatorial mount (manufactured by Software Bisque) as shown in Figure 4. The German-Equatorial configuration is characterized by a slight offset of the telescope relatively to the right ascension axis.

Telescope and mount balance are adjusted with two counterweights of 9 kg each. Balancing the telescope is a tricky procedure, which must be done carefully because it has direct consequences on the quality of telescope pointing. Also, adding or removing instruments and weights on the telescope affects the balance. So, when the telescope is adequately equipped and configured, it is better not to change it, even if this means leaving in place pieces of equipment that are not used very often. Hence, since the telescope served two missions (detection and spectral measurement) and uses two different CCD cameras, both are mounted simultaneously and the selection is done with a flip mirror (Figure 5). With this configuration, the telescope does not need to be balanced each time a different instrument is selected.

Table 1. *Characteristics of the Celestron CG-14 telescope*

Feature	Details
Optical design	Schmidt-Cassegrain
Optical diameter	14” (356 mm)
Focal length	3910 mm (F/ratio = f/11)
Limiting stellar magnitude	15.3
Resolution: Rayleigh	0.39 arcsec
Secondary mirror obstruction	4.5”
Optical tube length	31”
Optical tube weight	45 lbs

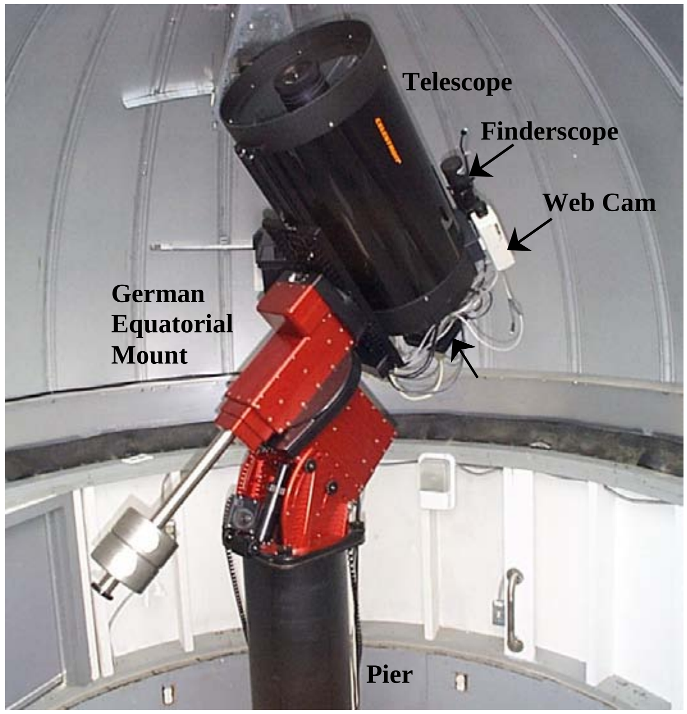

Figure 4. *Telescope and mount (Ref. 4)*

3.3 Measuring instruments

Optical instruments for image and spectral acquisition are installed at the base of the main tube of the telescope (Figure 5). This starts with an electric focuser, followed by a flip mirror and the two optical branches. As written above, the first branch has a CCD for satellite detection while the second one is equipped for spectral measurements.

3.3.1 The electric focuser

The sensor assembly starts with a ‘Temperature Compensating electric Focuser’ (TCF-S model manufactured by Optec) as shown in Figure 6. It can be programmed to automatically obtain accurate focus for a given range of temperature. The TCF-S is a robust Crayford style motorized focuser with high repeatability, no play and nearly zero backlash. A geared stepper motor rotates the drive shaft with one step rotation of the motor equal to a 0.00086 inch movement of the drawtube. The total travel of the drawtube is 0.6 inch or 7000 steps. A flip mirror is attached directly to the focuser and facilitates directing the light beam to either one of the two acquisition instruments used by the system.

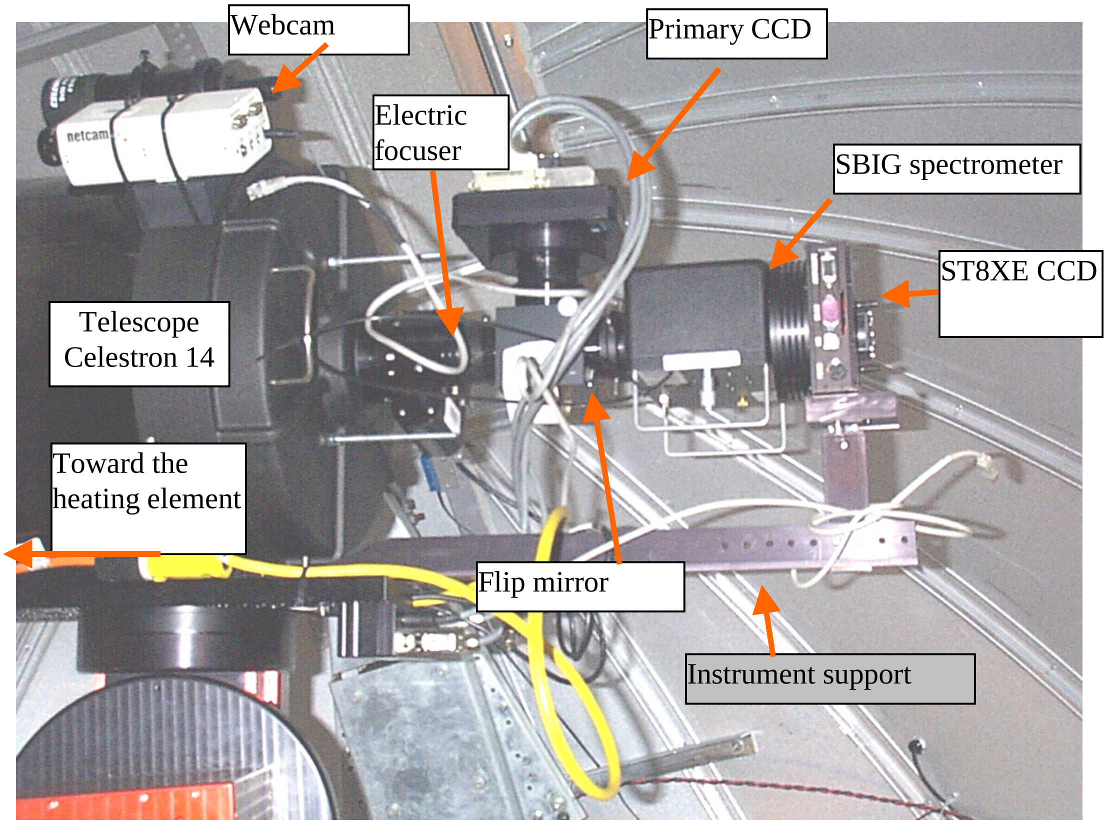

***Figure 5**. Physical arrangement of the instruments attached at the base of the telescope*

***Figure 6**. The Optec TCF-S electric focuser*

3.3.2 The flip mirror

The flip mirror is a part that facilitates simultaneously installing the two optical branches and switching easily from one to another. The mobile mirror can rotate from two adjustable stop positions and both optical branches maintain proper alignment.

Figure 7*. The Meade 647 flip-mirror system*

3.3.3 CCD cameras

The first acquisition instrument (Figure 8A) is an AP8P back-illuminated CCD camera (primary CCD) manufactured by Apogee Inc. The 1024x1024-pixel CCD has a chip size of 24.6 x 24.6 mm^2 and a quantum efficiency of 85% near the R band (red band). When coupled to the Celestron CG-14 telescope, the CCD field of view is 21.629 x 21.629 arcmin^2 and the pixel FOV of 1.27 arcseconds.

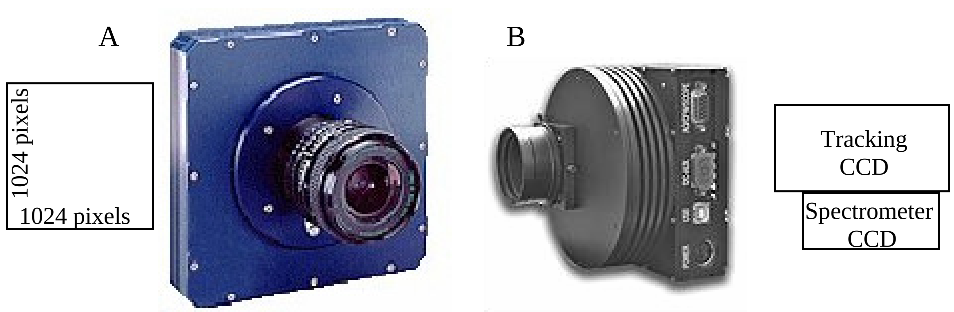

Figure 8. *The Apogee AP8P (A) and SBIG ST8XE (B) CCD cameras*

The second acquisition instrument (Figure 8B) is connected to a spectrometer (manufactured by SBIG) and is used for spectral acquisition purposes. It is composed of a SBIG ST8XE CCD camera and is equipped with an imaging CCD and tracking CCD chips. The 1530 x 1020 pixel imager CCD chip has an array dimension of 13.77 x 9.18 mm^2 and a quantum efficiency of 65 % near the R band. It is used for spectral acquisition. The second CCD has 657 x 495 pixels with an array dimension of 4.9 x 3.7 mm^2. When used in connection with the SBIG Self-Guided Spectrometer (SGS), this CCD can serve has a tracking instrument to ensure that the object that we want to observe remains in the slit of the SGS. The main characteristics of the CCD camera connected to the system are summarized in Table 2. Figure 9 shows the quantum efficiency curves for both the Ap8p and the ST8XE CCD chips.

The drawback of the SBIG ST8XE CCD is that the FOV of the tracker and imager are not the same but instead adjacent. For every astronomical application this is not an issue because it is not necessary that the (spectral) measured object and the tracked object be the same since both are celestial objects with exactly the same motion. Unfortunately, this is not the case for satellites, which have their own motion. In that case, the system should track and measure the same object simultaneously. Therefore, with this system, active tracking could not be used and only the telescope mount ability to track a satellite (using the TLE orbital parameters) was used without any correction. Due to the inability to use active tracking, satellite exposure times were often too short for this experiment's purposes.

Table 2. CCD specifications

CCD camera	Apogee AP8p	ST8XE imager	ST8XE tracking
Array dimension (mm^2)	24.6 x 24.6	13.77 x 9.18	4.9 x 3.7
Number of pixels	1024 x 1024	1530 x 1020	657 x 495
Pixel sizes (μ^2)	24 x 24	9 x 9	7.4 x 7.4
Read noise (e^- rms)	15	15	12
Gain (e^-/count)	4.5	2.3	0.72
Field of view with f = 3910 mm ($arcmin^2$)	21.629 x 21.629	12.107 x 8.071	4.274 x 3.221

3.3.4 The spectrometer

The Self-Guided Spectrometer (SGS) manufactured by SBIG was fixed between the flip mirror and the ST8XE camera. This spectrometer has physical dimensions of 10 x 12 x 20 cm and its weight with the camera is about 2.4 kg (Figure 10). It is specifically designed to operate with the ST-7/8/9 cameras. Both CCD chips installed in the ST8XE camera are used with the spectrometer. The tracking CCD is useful since it allows imaging the slit of the spectrograph. To obtain a spectrum, the object must be placed in front of the spectrometer entrance slit, which is imaged on the tracking CCD. The spectrum is acquired on a two dimension imaging CCD (Figure 11).

Two gratings are available with the SGS. The low resolution one has 150 rulings per mm and it gives a dispersion of 0.43 nm per pixel with a resolution of about 0.8 nm. A high-resolution grating may also be used and gives 0.107 nm per pixel with a resolution of about 0.22 nm. The spectral coverage is 320 nm and 75 nm for the low and high resolution, respectively. In addition to the gratings, two entrance slits (100 or 25 microns wide) can be used in the spectrometer. These slits have respective angular dimension 5.27" and 1.32" on the tracking CCD. We used a mercury lamp for wavelength calibration. Table 3 gives the main characteristics of the SGS spectrometer.

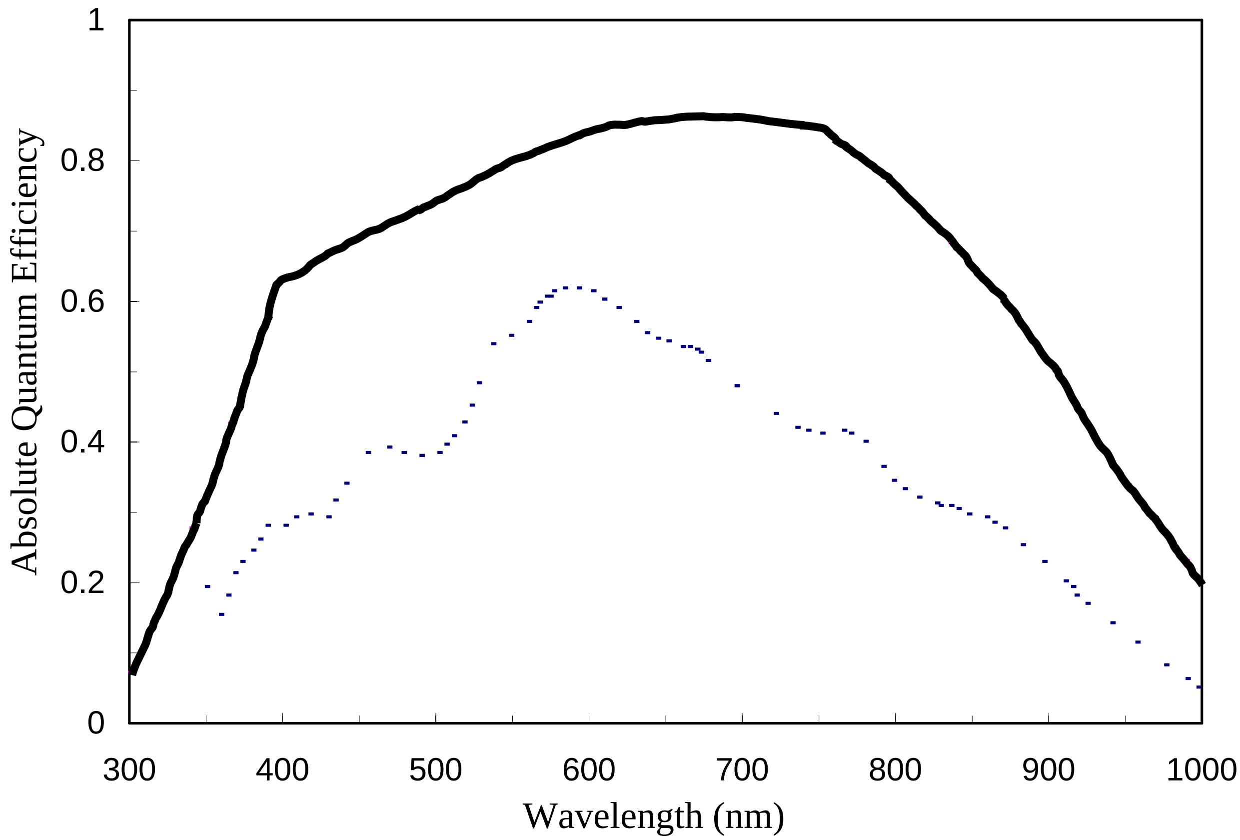

Figure 9. *Quantum efficiency curve for the AP8p back illuminated CCD chip (full curve) and for the ST8XE CCD chip (dot curve)*

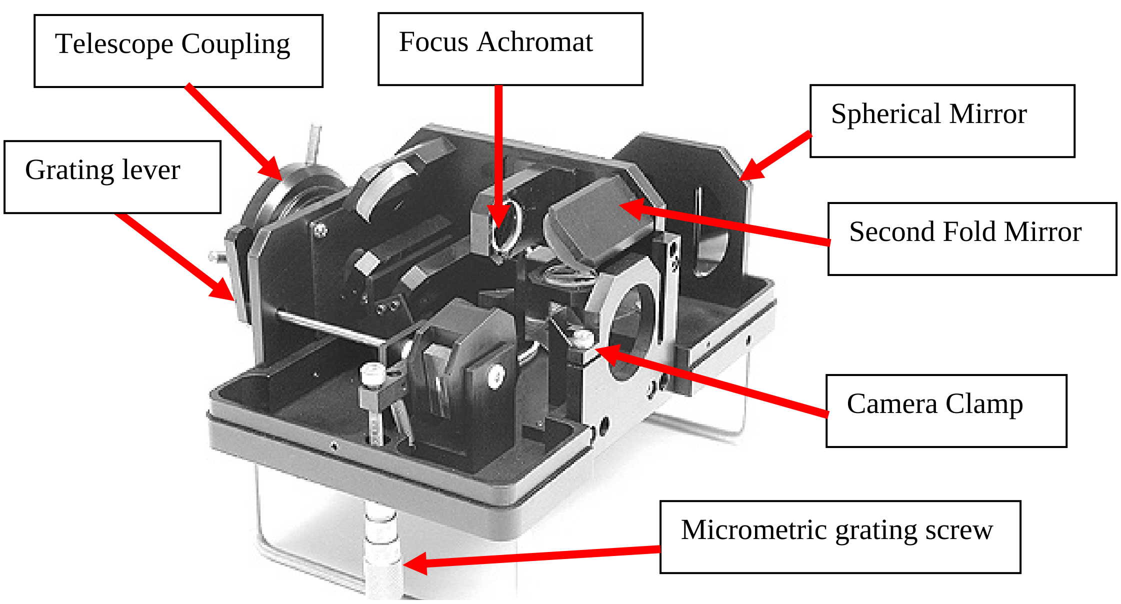

Figure 10. *The SBIG Self-Guided Spectrometer*

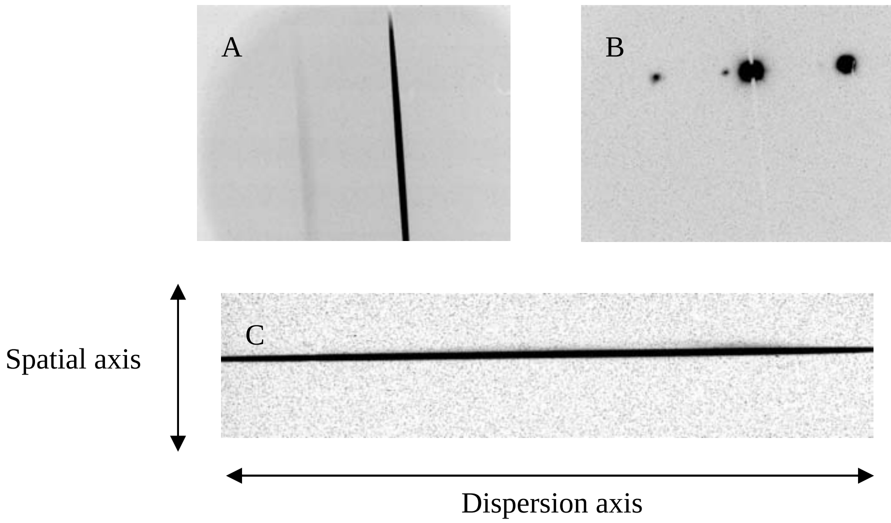

***Figure 11**. A) Image of the spectrometer slit back lighted with a led on the ST8XE tracking CCD. B) Superimposition of the star Seginus (Gamma Bootes) on the spectrometer slit. The three spots on each side of the star are ghost images. C) Two dimensional spectrum of Seginus acquired with the ST8XE imager CCD.*

***Table 3.** Physical characteristics of the Self-Guided Spectrometer*

Characteristics	Low resolution grating	High resolution grating
Dispersion (nm per pixel)	0.43	0.107
Resolution (nm)	0.8	0.22
Spectral coverage (nm)	320	75
Wavelength range (nm)	380 to 750	380 to 750
Entrance Slit (micron)	25 or 100	25 or 100

3.3.5 Instrument support

The Instruments attached at the base of the telescope were 70 cm in length. Without any appropriately support mechanisms, the weight of the structure results in important flexure of the instrument assembly. This causes an optical misalignment, which prevents light from entering the slit of the spectrometer. The alignment must be accurate since the light passes through a slit that is only 100 μm wide. In order to preserve the optical alignment, we installed an aluminium support on which the instrument structure rests (Figure 5). The support is provided with two micrometric screws, which allow correcting flexion in both two orthogonal axes. After adding that support, the position of the counterweight attached to the equatorial mount has been changed to preserve the static equilibrium of the telescope.

3.4 The software

All instructions given to the telescope were made from the astronomical software 'The Sky' (Fig. 12). This powerful software contains a graphical interface representing the sky in real time as it appears at the observation site. By pointing at a given object on this map, the telescope can be slewed to that object and tracks it for a given period of time. Apart the classical sidereal tracking mode, there also is a tracking mode where a satellite is tracked according to its orbital parameters (NORAD two-line element sets – TLE files). In order to accurately point the telescope, a model that takes into account mechanical errors has to be created. The Bisque's 'T-Point' (Fig. 12) telescope pointing software was used to correct problems such as flexion and torque of the telescope and mount as well as inaccurate polar alignment. Finally, we used the software 'CCDsoft' to acquire and analyze as well as to adjust the CCD camera conditions (cooling, binning, etc.).

The software 'Satellite Toolkit' (STK) was also used to optimize the number of satellites observed each night. STK provides sophisticated modeling and visualization capabilities. It was used in conjunction with the TLE files and observation conditions (observatory constraints, time of observation, etc.) mainly to determine visibility areas and time and to determine when a given satellite would enter our local sky.

For spectroscopy analysis, both 'Matlab' and the 'Astronomical spectral analysis and processing software Vspec' (developed by Valérie Desnoux, Ref. 5) were used.

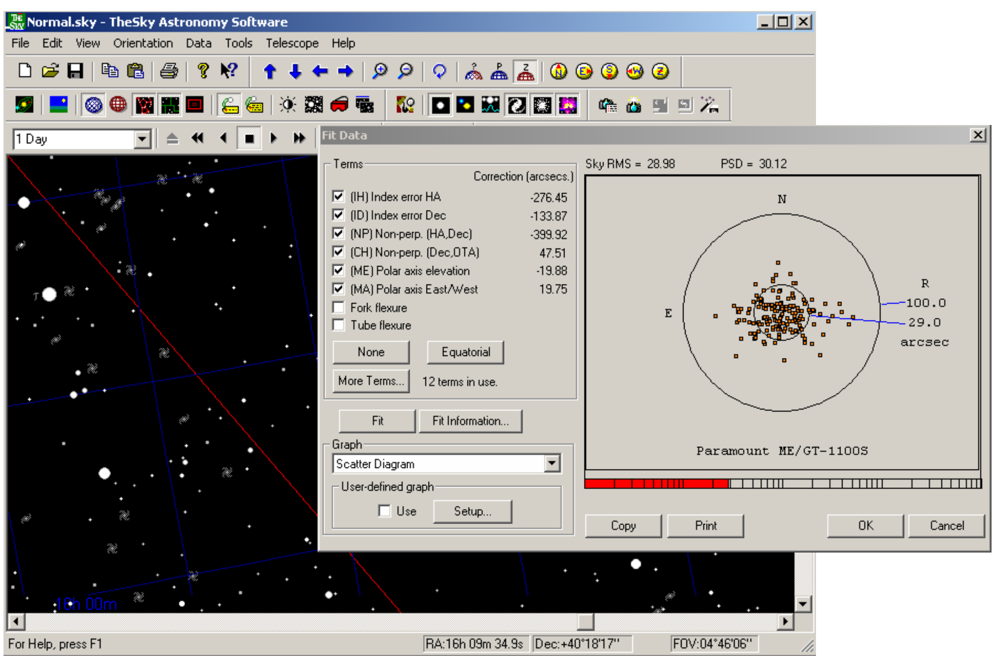

Figure 12. *The Sky and Tpoint software interfaces*

4. Calibration of the observational system

Before acquiring and analyzing any data, the observation system must be first well calibrated. Once the telescope is well balanced, the mechanical axes well aligned and the pointing software calibrated, the optical components must also be calibrated. This chapter describes the spectrometer calibration.

4.1 Focus adjustment

The image quality is directly dependent on the focus quality. Bad focus results in blurred (larger) objects, thus reducing the signal-to-noise ratio per pixel. Ambient temperature is the main factor affecting the focus of the instruments. First, a change in temperature affects the length and volume of the optical instruments by dilating (temperature augmentation) or contracting (temperature diminution) material. Second, physical characteristics of matter, such as refraction index, are directly linked to temperature. The resulting effect of temperature variation is the alteration of the localization where light beams focus. The system CASTOR-V is located at geographical latitude where large outdoor temperature differences are experienced. During the summer, night temperature may climb as high as 30^{o}C (an even hotter inside the dome) and fall as low as –35^{o}C during the winter. Moreover, during the same night, we may experience a temperature variation of as much as 10^{o}C. It then becomes necessary to adjust focus to compensate for these temperature changes.

Two independent systems allow for adjusting the position of the focal plane. For coarse focus adjustment, a turning knob (located at the base of the telescope) adjusts the position of the primary mirror. A coarse focus adjustment does not have to be performed every night, although it is necessary when there is a large temperature variation such as when there is season change. When the position of the primary mirror is adjusted, a finer focus adjustment is performed with the Optec electric focuser (see Figures 5 and 6). The main advantage of this focuser is that when the focus had been completed for two different temperatures, it is programmed to maintain it by (linearly) interpolating its current position based on the probed temperature.

The telescope could be used with either the Apogee AP8p or the SBIG ST8XE camera, which are selected with the flip mirror (Figures 5 and 7). In order to avoid performing an independent focussing procedure for each camera, the CCD positions are adjusted in such a way that the paths are the same for the two optical branches. Since there is no degree of freedom on the position of the spectrometer (with its ST8XE camera), it is focused (coarse and fine) first. Then, the focus of the Apogee AP8p CCD is adjusted with the adjustable-length cylinder that ties the CCD to the flip mirror.

4.2 Spectrometer calibration

After the spectrometer is mounted on the telescope, it is calibrated using the following steps. First, the slit focus is adjusted with the Focus Achromat until a sharp image of the slit (1 or 2 pixels wide) is projected on the tracking CCD. Then, the position of the imaged slit is centered on the tracking CCD. This is achieved by rotating the second fold mirror (Figure 10). Then the spectrometer is focused by translating the spherical mirror. Finally, a mercury lamp (that emits well-known spectral lines) is used to calibrate (in wavelength) the millimeter scale of the micrometric screw. Table 4 shows the relation between the micrometric-screw position and the wavelength measured at the center of the ST8XE imaging CCD.

Table 4. Wavelength calibration of the spectrometer micrometric screw

Micrometric screw position	Central wavelength at 765 pixels (nm)
500	324.1
550	533.6
600	743.1

The selection of two mercury lines of known wavelengths and the knowledge of their positions on the CCD array allow us to compute the dispersion relation for the low-resolution grating. This gives 0.4316 nm/pixel with the ST8XE CCD imager.

4.3 Comparison of sensibility of the AP8p and ST8XE cameras

By measuring the same stars with both cameras, we can compare them. This indicates a relation between the electronic flux and the magnitude for both cameras and allows quantifying their sensitivity differences. To do so, we observed a group of stars with the same observation conditions, i.e., sky condition, outdoor temperature, CCD temperature, etc. For a specific image, the stars are identified using the software ‘TheSky’, which also provides the star magnitudes up to a maximum of magnitude 16. A total of 55 stars, ranging from magnitude zero to magnitude 15.6, were used to obtain the relation flux-magnitude for the AP8p CCD (Figure 13).

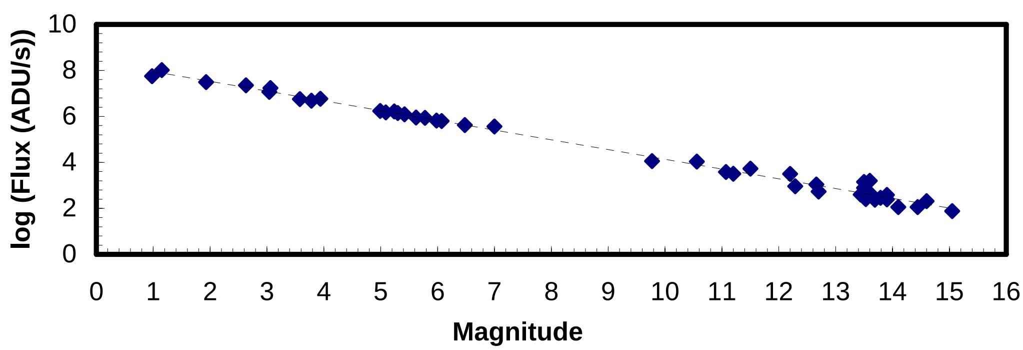

Figure 13. *Flux-magnitude relation for 55 stars imaged with Apogee*

By assuming that a linear trend applies also for the ST8XE CCD and by comparing the flux measured for several stars with both AP8p and ST8XE, we obtained the following flux-magnitude relations for the two CCD chips.

$$\text{Apogee: } \log(F_A) = -0.4244mA + 8.3772 \qquad \text{Eq. 1}$$

$$\text{ST8XE: } \log(F_S) = -0.4284m_S + 8.3772 \qquad \text{Eq. 2}$$

Where F_A, F_S, m_A and m_S refer to the flux (F) and magnitude (m) measured with AP8p (A) and ST8XE (S).

For a given star of magnitude m, this leads to the following link between the flux measured with Apogee and ST8XE.

$$F_S/F_A = 10^{-0.004m} \qquad \text{Eq. 3}$$

5. Results

We tried to perform spectral acquisitions for both geostationary and low orbit satellites. If some success was achieved with geostationary satellites, this was not the case for low Earth orbit satellites. The problem occurs mainly because it was not possible to center and maintain the satellite in the spectrometer entrance slit. Indeed, to obtain spectra, two conditions should be met. First, the satellites must be accurately centered in the spectrometer entrance slit and, second, it must be tracked with accuracy. The current system design does not allow both operations at the same time. The propagator used by the software The Sky is accurate enough to track the satellite for a short period of time. However, the TLE data provided by NORAD (that gives the updated orbital parameters of the satellite) are not accurate enough to point the satellite directly into the spectrometer slit without a fine pointing adjustment. The issue with the current design is that the satellite cannot be imaged and have its spectrum acquired at the same time. This would require a different optical design with a dual telescope (one for pointing and tracking and one for the acquisition), a stronger telescope mount and probably a larger dome.

5.1 Expectancies for geostationary satellites

The choice for geostationary satellites is justified mainly because these satellites are the easiest to track. All we have to do is to point at the object and switch off the sidereal tracking.

The problem with geostationary satellites is their lack of brightness because of their distance (36 000 km). The factors that contribute to the brightness of satellites include shape, bidirectional reflection coefficient, cross section, material (spectrum), phase angle (angle between the sun, the satellite and the observer) and whether the satellite is rotating or not. Satellites are generally at their brightest at large phase angles (at angles, between sun-satellite-observer, which approach 180°), since the observer is at the best location to best perceive the satellite. Hence, the best time to search for geostationary satellites is when they are directly at the opposite of the sun.

Most operational geostationary satellites are large, but they are all over 36 000 km distant from the observer and few become brighter than magnitude +11 (many are in fact magnitude +13 or fainter). Theoretically, we can image a point source object of 19th magnitude in ten seconds with a SNR of one sigma with the CASTOR-V observational system. By using star data that we obtained in photometric condition with the observing system, we found that the limit of sensitivity of CASTOR-V would allow imaging a point object of 18.6th magnitude in ten seconds at one sigma (SNR) with the AP8p CCD. Considering that in good observing conditions, some geostationary satellites may become as bright as 10th magnitude, it is reasonable to suppose that spectrum acquisition of geostationary satellites is possible.

5.2 Spectrometer set up

The magnitude of geostationary satellites is subject to great variations depending mostly on the satellite phase angle. Also, their distances prevent them from being very bright. In order to obtain spectra of geostationary satellites, some precautions are then required. Apart from observing in good sky conditions, a precise adjustment of the optical system must be performed. This includes focus calibration and spectrometer configuration.

Two slits are available with the spectrometer, a large (100 μ) and a narrow slit (25 μ). The 100 μ slit was chosen to maximize the amount of light that enters into the spectrometer and increases the likelihood of maintaining the satellite inside the spectrometer FOV while observing. Indeed, even if geostationary satellites are relatively easy to follow, mechanical flexures in the instrument may occur, which would change slightly (but surely) the telescope pointing. Also, most of the GEO satellites do not have an orbit with a perfect zero inclination, which produces a small residual motion with a sine wave pattern above and below the equatorial plane. We also used the low spectral resolution grating to perform acquisition in order to increase the integrated intensity per pixel on the spectrum.

After choosing the slit size and grating type, a careful adjustment of the micrometric grating screw must be performed. This screw controls the rotation of the grating and allows translating the waveband covered by the CCD. To increase the chance of acquiring a spectrum with good signal-to-noise ratio, it is necessary to select the waveband where solar illumination is maximum. To achieve this, a sun-type star (G2 spectral type stars) is observed. Several low-resolution spectra are acquired with different positions for the micrometric grating screw. All spectra were acquired with the same exposure time. By comparing the results, we found that the best position of the micrometric screw, which gives the maximum flux on the CCD, is 550 (an uncalibrated graduation on the screw that should provide coarse wavelength estimation). This position of the micrometric screw gives a central CCD position corresponding to 533.6 nm with a dispersion of 0.4316 nm/pixel. Therefore, the micrometric grating screw was adjusted to position 550 to perform spectral acquisition of geostationary satellites.

5.3 Observed geostationary satellites

The period allocated for spectral acquisitions with the CASTOR-V equipment was not long enough. Most of that period was consumed by mechanical and calibration matters. When the spectrometer was finally operational, only three geostationary satellites could be observed before removing the spectrometer (the installation had to be reconfigured in its original setup for another project). The observed satellites were: Amazonas, Nimiq 2 and Rainbow 1. Those three satellites are found at an altitude near 36 000 km and they are thought to be the brightest geostationary satellites that can be observed. A brief description of each satellite is given below. If the installation were still available, it is not sure that other satellites could have been observed because the telescope and CCD were used at their extreme limit of sensitivity.

5.3.1 Amazonas

Amazonas is a telecommunication satellite used mostly by South American countries, especially Brazil. It also serves for transatlantic communication between America and Europe. Amazonas belongs to the Espanola Society Hispasat and has been built by E.A.D.S. Astrium on a platform Eurostar 3000. The launching mass of Amazonas accounts for 4500 kg. Its height, length and width are 5.8 m, 2.4 m and 2.9 m, respectively. After deploying its solar panels, it spans 35 m. Amazonas orbital position is 61^o west. It has 19 repeaters in the C band and 32 repeaters in the Ku band. Amazonas financial support comes mainly from the European Spatial Agency (E.S.A). This satellite is supposed to be commissioned for 15 years.

5.3.2 Nimiq 2

Nimiq 2 is a communication satellite that mostly covers Canada and the continental United States (CONUS). It was manufactured by Lockheed Martin Commercial Space Systems. Its minimum service life expectancy is about 12 years. It has a mass of 3600 kg and has been built on a platform A2100AX. Nimiq 2 dimensions are height = 5.8 m, length = 2.4 m, width = 2.4 m. Nimiq 2 is a high power Ku/Ka-band satellite that features 32 active 24 MHz Ku-band transponders with 120 watt power amplifiers. It also has a Ka-band payload that will provide broadband services. Nimiq 2 orbital position is 91^o west.

5.3.3 Rainbow 1

Rainbow 1 is a high power Ku-band direct broadcasting satellite manufactured by Cablevision from Lockheed Martin. It uses a platform A2100AX and is designed to provide direct broadcast services across the continental United States (CONUS). Its orbital location is 61.5^o west and its life expectancy is 18 years. Rainbow 1 mass is 4328 kg.

5.4 Data reduction and spectral calibration

Even with the brightest satellite, every satellite spectra has a very low signal-to-noise ratio. In order to facilitate subsequent analysis, an accurate data reduction had to be performed on the rough data. In the following section, the main steps of data reduction applied on each individual spectrum described.

5.4.1 Subtraction of the dark signal for each individual image

The dark count of a CCD occurs because even in the absence of light, electrons accumulate in the CCD pixels, as if photons were indeed falling onto the array. This noise is indistinguishable from the desired photon signal. The dark count can be reduced first by cooling the CCD. This decreases the thermal activity of electrons on the CCD. Hence, all the acquisitions were done with a chip cooled to –30C, a temperature where the dark current is minimum. Dark frames were also acquired to further reduce the analysis errors. Dark frames are images taken during a given period in dark conditions (shutter closed). By supposing that the readout noise and remaining dark count noise are somewhat repeatable, the dark frames can be subtracted from each individual astronomical image. This enhances the signal contrast by removing the image bias (background).

5.4.2 Line crushing along the spatial axis

An example of a spectral image acquisition is presented in Figure 11c. From the left to the right, this is the wavelength or ‘dispersion’ axis. From top to bottom, this is the slit projection and the pixels need to be summed in that axis to increase the signal-to-noise ratio. By performing this summing, the image is reduced to a simple spectral profile such as shown in Figure 14.

5.4.3 Wavelength calibration

The wavelength relation, along the dispersion axis of the CCD, needs to be defined for a specific position of the micrometric screw of the spectrometer diffraction grating. This is performed by observing a calibration mercury lamp with the spectrometer. Given the known wavelength of two mercury spectral lines and by assuming that the wavelength dispersion is linear, the pixel coordinate can be linked to a wavelength value all along the dispersion axis.

5.4.4 Correction of CCD spectral response and atmospheric transmission

The last step consists in correcting every spectrum for the non-uniformity of the CCD spectral response and for the atmospheric transmittance. This combined atmospheric and CCD spectral response is determined by comparing the known theoretical profile spectrum of a star of reference with the acquired spectrum of one of the same spectral type that was observed in the same sky area as the acquired satellite. Normally, the continuum distribution of stars of a same spectral type is nearly the same. Differences are related mainly to the non-linearity of the spectral response and wavelength dependent atmospheric transparency. Basically, the ratio between the relative intensity of the theoretical and experimental profiles is the spectral response function, such as illustrated in Figure 14. The correction for CCD spectral response is done by dividing each newly acquired spectral profile by this response function. The star ‘Seginus’ was one of the stars used to perform such a spectral correction, as illustrated in Figure 11.

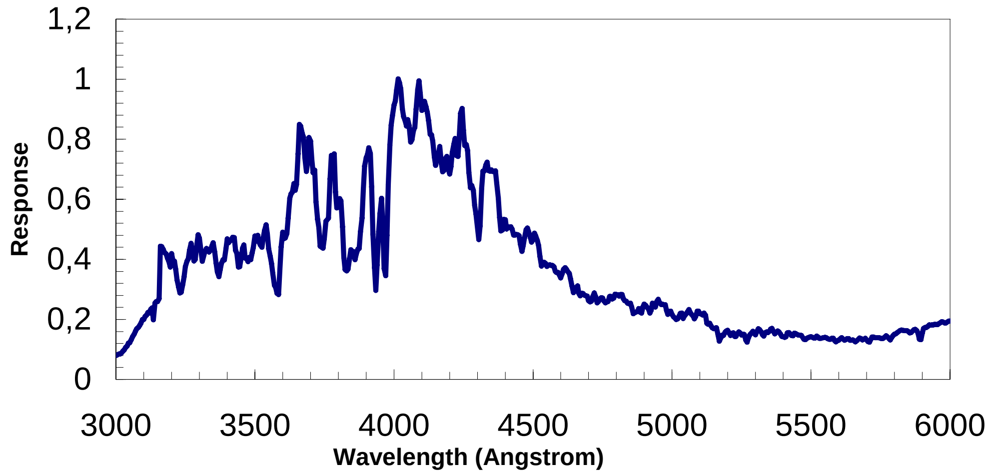

***Figure 14.** Normalized CCD ST8XE spectral response*

5.5 Profile averaging

For the three studied geostationary satellites (Amazonas, Nimiq2 and Rainbow 1) several individual spectra were acquired. Examples of raw spectra are shown in Figure 15. After correcting and calibrating each individual raw spectrum using the techniques described above, the next step consists in combining all spectra belonging to a given satellite to reduce the noise. Afterwards, the resulting spectrum is normalized and a filter is fitted to extract the profiles that could show differences in the trend of the three satellite continuums (Figure 16).

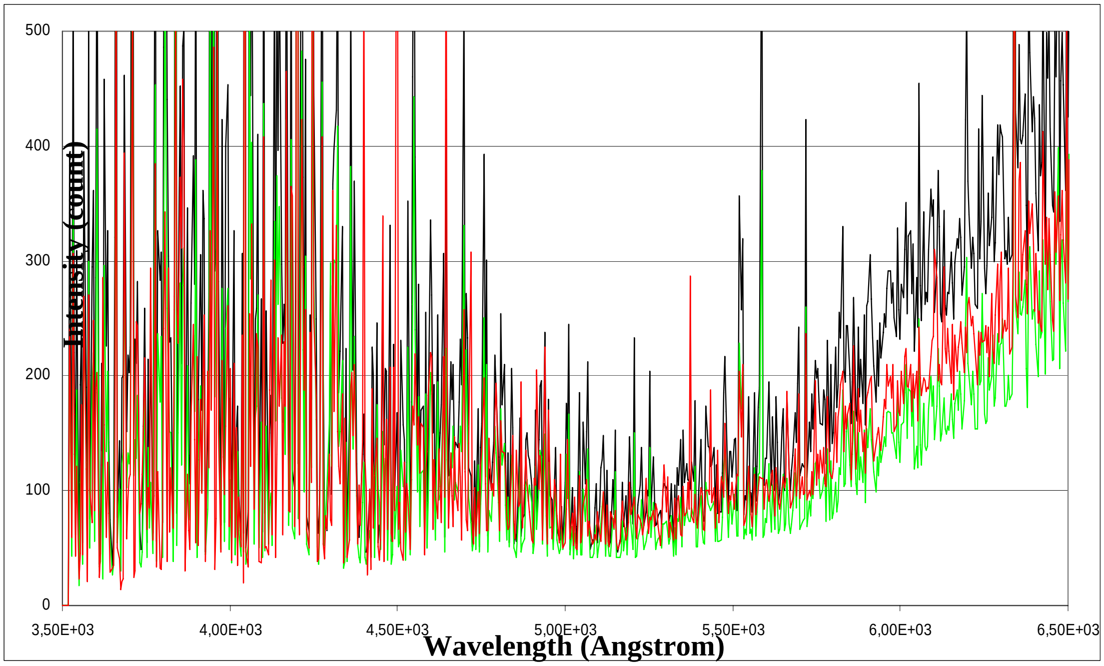

Figure 15. *Raw spectrum for Amazonas (black curve), Nimiq 2 (green curve) and Rainbow 1 (red curve)*

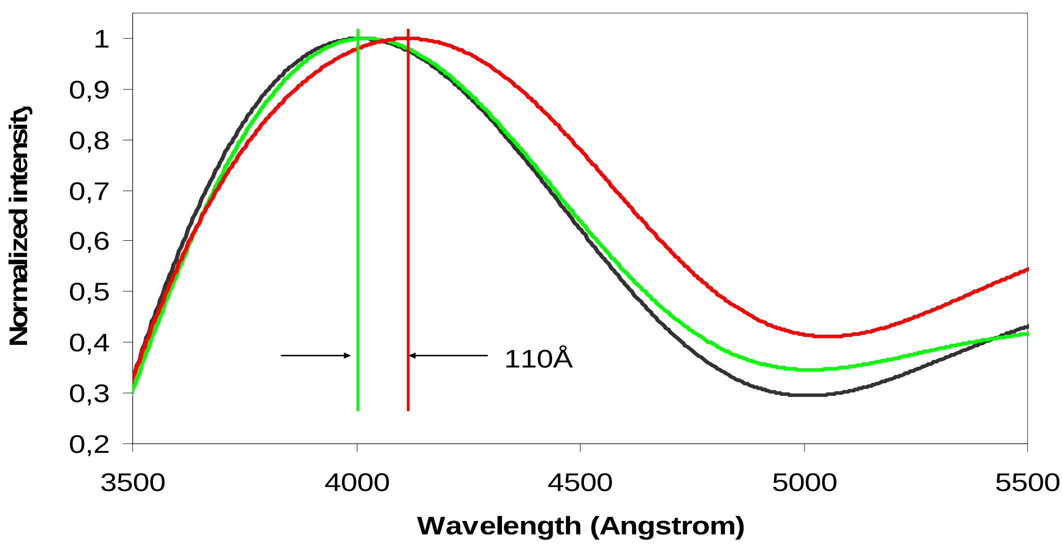

Figure 16. *Normalized continuum spectrum for Amazonas (black curve), Nimiq 2 (green curve) and Rainbow 1 (red curve)*

6. Analysis

Figure 15 shows that the continuum of Amazonas and Nimiq 2 are fairly similar. However, the spectrum of Rainbow 1 is red-shifted significantly in comparison with the other two satellites. In the present section, the reliability of these results is discussed.

6.1 Signal-to-noise ratio of the combined spectrum

In order to evaluate the limit of sensitivity (in magnitude) of the observation system, it becomes necessary to calculate the signal-to-noise ratio of the acquired data. The signal-to-noise can be defined as followed (Ref: Space Telescope Science Institute):

$$SNR = \frac{N_{cont} \cdot t}{\sqrt{N_{cont} \cdot t + p \cdot N_{sky} \cdot t + p \cdot N_{dark} + \frac{p}{f_s} \cdot n \cdot \sigma^2}} \qquad \text{Eq. 4}$$

Where:

SNR = The signal-to-noise ratio.

N_{cont} = Signal in electrons per seconds in the spectral continuum for a star of given magnitude m.

N_{sky} = Mean signal (in electron per second) of the sky located under the star spectrum.

N_{dark} = Dark signal of the CCD in electron per second.

p = width (in pixels) of the binning zone measured perpendicularly to the dispersion axis.

f_s = Binning factor of the CCD in the direction perpendicular to the dispersion axis.

σ = the standard deviation of reading noise of the CCD camera

t = total exposure time which takes into account image combination.

n = Number of images used for combination to reach the total exposure time t.

Equation 4 is used to compute the signal-to-noise ratio of the combined spectrum for the three investigated geostationary satellites; Amazonas, Nimiq 2 and Rainbow 1. Results are summarized in Table 5

Table 5. Signal-to-noise ratio for the combined spectrum of Amazonas, Nimiq 2 and Rainbow 1

Satellite	Total exposition time (s)	Number of combined spectrum	SNR
Amazonas	1320	10	19.6
Nimiq 2	1080	10	19.0
Rainbow 1	1080	6	20.0

6.2 Magnitude of the three geostationary satellites

In addition to the spectra acquired with the ST8XE imager for Amazonas, Nimiq 2 and Rainbow 1, images were also acquired for these three satellites with both the AP8p and the ST8XE tracking CCDs. Since images and spectra have been acquired in a short period (a maximum of a few minutes of interval), the satellite magnitudes could have been measured. To do so, the brightness of known stars (integrated over several pixels) was measured and the relation between the electronic flux and stellar magnitude were established. Then, using the total satellite signals (average of ten individual measurements for each satellite), their magnitudes were evaluated and listed in Table 6.

Table 6. Magnitude evaluated for the Amazonas, Nimiq 2 and Rainbow 1 satellites

Satellite	Magnitude
Amazonas	10.92
Nimiq 2	10.32
Rainbow 1	10.15

6.3 Magnitude and time acquisition requirement for the acquisition of significant spectrum

The results from the last section give a relation between satellite magnitude, spectrum time acquisition and signal-to-noise ratio. Based upon these results, we looked for a relation between the satellite magnitude and the mean signal arising from the section of interest of each spectrum (N_{cont} in equation 4) (Figure 17).

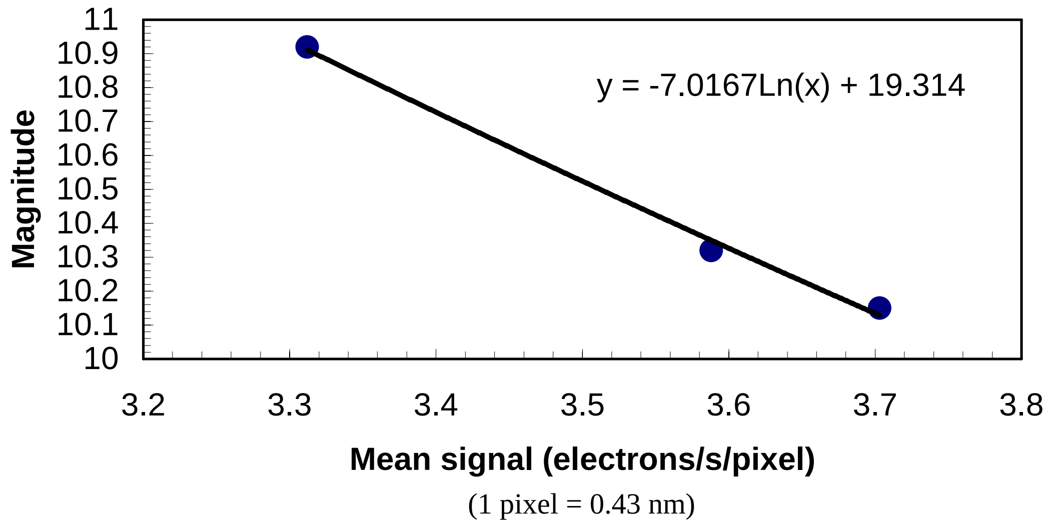

Figure 17. *Magnitude of Amazonas, Nimiq 2 and Rainbow 1 against N_{cont}*

The dependence linking the three points in Figure 17 leads to the conclusion that a magnitude 10 object corresponds to a mean signal of N_{cont} = 3.77 electrons/second/pixel (1 pixel = 0.43 nm) in the region of interest of the spectral continuum (around 550 nm). This means that obtaining the spectrum of a magnitude 10 object with SNR = 10 would require 2.8 minutes of time acquisition. Note that it is recognized in the astronomical community that a SNR of 10 is the minimum required to distinguish a star type using its spectral continuum, and this same criterion is used for the satellite classification problem (as a reasonable first approximation). These 2.8 minutes of integration time is inferior to the mean time during which tracking efficiency of the observing system keeps a GEO object in the spectrometer slit without mechanical readjustment (around 5 minutes). From these considerations, it appears that having a single exposition spectrum with SNR ≥ 10 is achievable for objects brighter then magnitude 12.1.

6.4 Improvement of the CASTOR-V spectroscopic capabilities

Typically, geostationary satellites will be in the magnitude +11 to +14 range (or dimmer). This makes the present CASTOR-V system suitable for performing spectral acquisition for only a limited sample of geostationary satellites. For non-geostationary objects, the system is inoperable due to the lack of tracking capabilities. However, this study allowed establishing the complexity of the task and determining what theoretical system limitations. The following are suggestions that will have to be considered if another system should be designed for this specific task.

6.4.1 Spectrometer support

Good telescope balance is a major issue for pointing and tracking accuracy. Preliminary balance procedures was performed by adjusting the position of the mount counterweights according to the total weight of the observational system. This includes the telescope, mount and all the observational instruments (including the support) attached to it. After performing this operation, the next step consists in refining the pointing with a TPoint model. These steps have been performed on the system and gave good results (best pointing accuracy of 20 arcsec).

Improvement must be achieved concerning the spectrometer support (Figure 5). Indeed, we noted that some flexions happen in the support while moving the telescope to a given target. These flexions continue even when the telescope is not moving as when staring at a geostationary satellite. The amplitude of these flexions depends on the orientation of the telescope, but we did not quantify it yet. However, we are fairly confident that these flexions are the major limit to maintaining an object at the same position on the CCD chip. Recall that we were able to keep a geostationary satellite on the spectrometer slit during an average of 5 minutes. To increase the stability of the system, it is necessary to design and build a new support that will be less subject to flexion.

6.4.2 Software interface

The software used to track the satellite was quite good, but if the pointing of the system was not perfect, then the system would track just beside the object and the spectrometer would see nothing. When in tracking mode, there was no way to introduce position perturbations into the tracking software to achieve pointing corrections. What the tracking software should be able to do is: 1) track a satellite using its orbital parameters, 2) acquire an image with the tracking CCD, 3) evaluate the “number of pixels” offset (from the spectrometer entrance slit) and 4) introduce pointing correction into the tracking software. Then, the spectrometer could start the acquisition process while the tracking CCD is periodically interrogated to maintain tracking accuracy. For now, the software ‘TheSky’ allows only a blind satellite tracking based on the orbital calculation without correction in the tracking loop. This commercial software should be modified to accommodate tracking sensor updates while in pursuit mode.

6.4.3 Utilization of two telescopes for tracking and imaging

If it was already very difficult to acquire spectra of geostationary satellites, then it is almost impossible to acquire the spectrum of a fast moving satellite with the current system design. The satellite cannot be imaged at the same time on the spectrometer CCD and on the tracking CCD, and these CCDs share the same focal plane surface. Both CCDs are placed one beside the other. This is correct for any other astronomical application because, when the spectrum of an object (star, nebula, etc.) is being acquired, other stars can be used for tracking correction since all celestial objects move together as a rigid body. However, for a satellite, there is no other object that can be used as reference. Therefore, the satellite must be acquired at the same time by both CCDs.

A first solution could consist in placing a beam splitter within the optical path and having two independent CCD cameras. However, this would put a lot of weight on the optical tube (behind the focuser) and it would also be difficult to balance the two optical paths and adjust the focus for both cameras simultaneously. Furthermore, the spectrometer is very photon limited and the beam splitter would have to divide the optical beam in the right proportion, i.e., most of the photons towards the spectrometer.

A better system would consist of two independent telescopes mounted on the same mount (preferable a fork mount). This would make a system easy to align and each sensor would be easy to adjust. Furthermore, both optical sizes could be chosen accordingly to the sensor sensitivity requirement, i.e., a large telescope for the spectrometer and a smaller one for the tracking CCD.

6.4.4 Using a larger primary mirror

The photon flux reaching the detector is directly related to the area of the primary mirror. Let us observe how the performance of the telescope would be improved by using a larger primary mirror. To do so, the theoretical limited magnitude is computed for discerning an object with a S/N = 1 in an image acquired during 10 s with the AP8p CCD. Figure 18 shows what is expected in function of the primary mirror diameter (without corrections made by an adaptive optics). As can be seen, a primary mirror with a diameter equal to 35 cm leads to a limit magnitude of 18.2. By enlarging the mirror to 60 cm, the dimmest acquirable object would be 18.8. This small difference of only 0.6 magnitude between the two mirrors clearly shows that, when a larger mirror is used, the noise component prevents considerable enhancement of the sensibility. The principal source of noise at CASTOR-V is related to the sky and dark signal.

Figure 18 also shows that enlarging the primary mirror to diameter up to 4 m and 8 m would only increase the sensibility limit to 21.0 and 21.8, respectively. This last result shows the importance of improving the observation condition of the system when considering the use of large primary mirrors. Basic improvements imply choosing a good observation site for the system (low humidity level, light pollution free, etc.), a well-designed observatory (well ventilated dome, low thermal turbulence, mechanical stability of the telescope, good detector, etc.) and, in some cases, a system correction for atmosphere turbulence (adaptive optics). All these improvements would increase the sensibility limit of the observation system by reducing the main source of noise and by increasing the spatial resolution of the telescope. However, all these suggestions implies a very high cost observatory and one of the goals of the current study was to verify if satellite spectra could be acquired with low cost equipment and not how to acquire spectra at any cost.

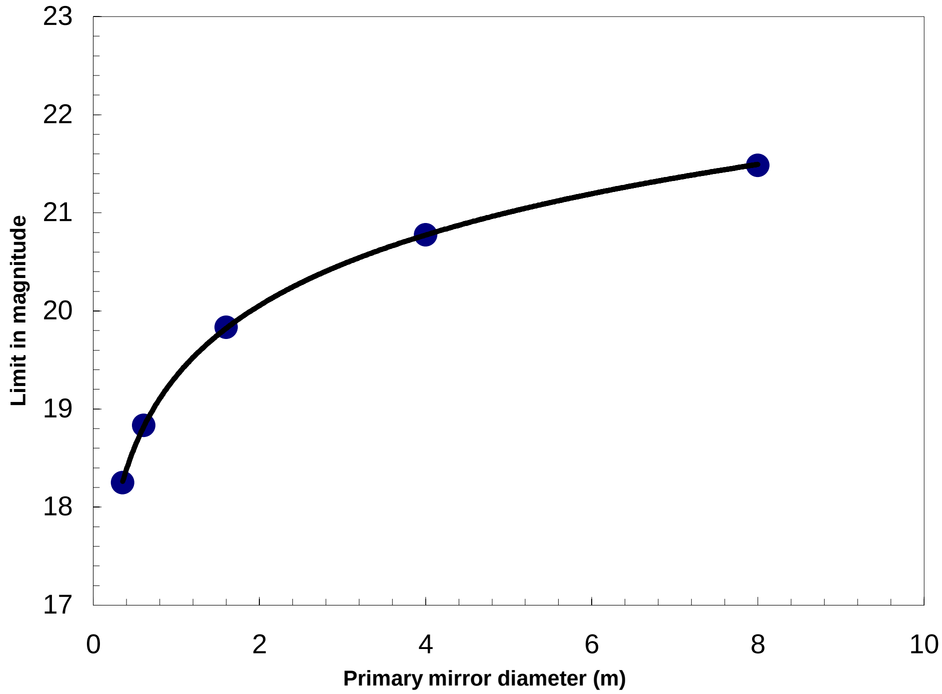

Figure 18. *Theoretical limiting magnitude achievable during 10 seconds with Apogee for a signal-to - noise image of 1 in function of the primary mirror diameter*

Improving the observation site for CASTOR-V is a major issue if building a large observatory is considered in the future (primary mirror larger than 1 m). Currently, the proximity of CASTOR-V to the highly illuminated urban area of Quebec City causes a major light pollution problem, which is the main cause of sky illumination. High light pollution level greatly reduces the capability to image dim objects. A secondary problem is related to the average high humidity level measured at CASTOR-V site during one year of trial. Humidity causes enhanced light scattering, which degrades the quality of visibility for observation. A good observational site would then have to be dry and (relatively) light pollution free.

The observatory design of CASTOR-V could also be improved. First of all, physical conditions (temperature, humidity level, etc.) inside the dome must reproduce as much as possible the outdoors conditions. To do so, basic operating precautions can be taken such as opening the dome shutter a few hours before performing observations. Also, a dome configuration with many aperture windows helps in rapidly achieving (few minutes) the outdoor in-dome temperature uniformity. The new generation observatory domes are built this way (Figure 19).

***Figure 19**. Sunset view of the Mont Megantic observatory. The telescope inside the dome has a primary mirror diameter of 1.6 meter. Note the presence of ventilating windows surrounding the dome.*

It would also be desirable to decrease (as much as possible) the emissivity of the observatory components (telescope, dome) in order to avoid thermal turbulence inside the dome and especially in the vicinity of the primary mirror. In that perspective, ventilating the primary mirror would help to reduce thermal turbulence.

CCD camera efficiency could also be improved. For example, the quantum efficiency of the ST8XE camera has a maximum around 60% at 600 nm. It is not rare today to find CCD cameras for which quantum efficiency rises up to 90%. Also there are CCDs with lower dark signal and readout noise and larger gain.

Low cost telescopes, without adaptive optics system, remain the simplest and most efficient way to perform satellite spectroscopy. What we suggest for obtaining the capability to observe fainter magnitude objects is increasing the primary mirror to about 24 inches, which still represents a relatively inexpensive telescope. Along with a better CCD detector, one could expect obtaining spectra for objects of one magnitude fainter than what was observed with the current system. This means that a few dozens of satellites could be measured compared with the only three ones that were bright enough to be acquired with the current system. Then, the concept of spectral identification could be adequately investigated.

7. Conclusions

The limits of capability (for spectral acquisitions) of the CASTOR-V observatory have been estimated and the results are presented in this report. Spectra were successfully acquired for three of the brightest geostationary satellites. Now that the limits of system sensitivity are known and understood, it is believed that other geostationary satellites could have been observed but, unfortunately, the spectrometer had to be dismounted and the telescope returned to it primary assignment task (detection).

These spectra were acquired with sufficiently good signal-to-noise ratios to allow physical analysis and comparisons. It appears that Rainbow 1 definitively has a different spectrum than Amazonas or Nimiq 2. From these measurements, it was also estimated that the limit of sensitivity of the system is magnitude 12.2 for an (spectral) acquisition time of 5 minutes and a SNR of 10.

The current tracking capabilities of CASTOR-V make it possible to obtain spectra for geostationary objects only. Since those satellites have magnitudes ranging typically from 11 to 14 (and fainter), it is obvious that the CASTOR-V spectral acquisition capability is limited to a small range of satellites. The current study briefly demonstrates the concept.

However, this experiment gives us some indications regarding the design of a better (low cost) system that would be suitable for such a task (maybe not a fully operational station but at least a far better concept demonstrator). The optical performances of the CASTOR-V system could be improved with some modifications (mechanical adjustment, increasing the similarity of the observational conditions, such as temperature and humidity level, outside and inside the dome). The tracking software will have to be updated to be able to insert tracking corrections while a satellite is tracked using its theoretical calculated position (when using its orbital parameters).

If a new system could be designed from scratch, it is recommended to use a dual telescope to be able to achieve the tracking and spectral acquisition tasks simultaneously. The use of a telescope with a 24-inch primary mirror would highly improve the measurement capability without highly increasing the cost. Because of the cost, it is not recommended to use a larger telescope on the current site, which suffers from poor observation conditions (moisture and light pollution). If a bigger telescope is considered, then definitively another site will have to be chosen. Finally, a better CCD camera should be used. There are CCDs with better quantum efficiency and lower dark current and reading noise. This is probably the best investment that could be performed (best bang for the buck for this application).

Such a 24-inch telescope should be able to acquire a few dozen of geostationary and Molniya satellites and be able to fully demonstrate the possibility of identifying them by measuring their spectrum. However, it is already known that such a system will not have the capability to meet operational demands. A real operational system would require a telescope with several meters of aperture and would cost several tens of millions of dollars.

To conclude, the current experiment has proven that difference of colour between satellites can be measured. However, these measurements were not accurate enough to establish if the satellites can be definitively identified by their spectral signatures; there were too few bright enough satellites and too few measurements performed during the time the telescope could be used for this task to make any definitive claims. Because of the difficulties inherent to this experiment, because of the major investment a better observatory would require, and because the value added has not yet been demonstrated, it is recommended not to pursue this experiment any further, at least not with amateur class astronomical equipment. The proof of concept experiment could be pursued with a larger telescope, but even in that case, it is not certain that such an investment could lead to an operational system.

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Glossary

Technical term	Explanation of term
DND	Department of National Defence
DSpaceD	Defence Space Directorate
SoSP	Surveillance of Space Project
SSN	Space Surveillance Network
TLE	Two Line Element set

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In the surveillance of space context, the satellites positions must be reacquired frequently to maintain an accurate knowledge of their orbital parameters. However, it is not rare to acquire several satellites in the same image (particularly in the geostationary belt) and it is not possible to identify each one of them. In such a case, important errors can be introduced into the database if wrong associations are made. Therefore, it is really important to be able to identify each satellite to make valid updates.

For this end, the experiment described in this report tried to demonstrate that 1) satellites identification can be made using their spectral signatures and 2) these spectrum can be acquired with a small telescope. However, even if difference in color could be observed, the measuring system was not sensitive enough to really demonstrate this hypothesis and too few observations were done (with only the brightest geostationary satellites) during the period where the telescope was available for this experiment. This report presents the few results that were obtained, explains the encountered difficulties and makes recommendations about the minimal equipment requirement that should be used if the experiment should be done again.

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Dans le contexte de la surveillance de l'espace, la position des satellites doit être acquise fréquemment pour maintenir une connaissance précise de leurs paramètres orbitaux. Cependant, il n'est pas rare d'acquérir plusieurs satellites dans la même image (particulièrement dans la ceinture géostationnaire) et qu'il n'est pas possible d'identifier chacun d'eux. Dans un tel cas, des erreurs importantes peuvent être introduites dans la base de données si de mauvaises associations sont faites. Donc, il est très important d'être capable d'identifier tous les satellites afin de faire correctement les mises à jour.

À cette fin, l'expérience décrite dans ce rapport a essayé de démontrer que 1) les satellites peuvent être identifier en utilisant leurs signatures spectrales et 2) ces spectres peuvent être acquis avec un petit télescope. Cependant, même si des différences de couleurs ont été observées, le système de mesure n'était pas suffisamment sensible pour réellement démontrer cette hypothèse et trop peu d'observations ont été faites (avec seulement les satellites géostationnaires les plus brillants) pendant la période où le télescope était disponible pour cette expérience. Ce rapport présente les quelques résultats qui ont été obtenus, explique les difficultés qui ont été rencontrées et fait des recommandations à propos de l'équipement minimal requis qui devrait être utilisé si l'expérience devait être refaite.

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